

Unconventional proximity effects and pairing symmetries in cuprates caused by conventional phonons

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Giant and nil proximity effects and unconventional symmetry of cuprate superconductors are explained as a result of the strong Fröhlich interaction of holes with c-axis polarised optical phonons acting together with an anisotropic nonlocal deformation potential.

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A number of observations point to the possibility that many high- T_c cuprate superconductors may not be conventional Bardeen-Cooper-Schrieffer (BCS) superconductors, but rather derive from the Bose-Einstein condensate (BEC) of real-space pairs, which are mobile small bipolarons [1]. A possible fundamental origin of such strong departure of the cuprates from conventional BCS behaviour is the Fröhlich electron-phonon interaction (EPI) of the order of 1 eV [2], routinely neglected in the Hubbard U and t-J models of cuprate superconductors [3]. This interaction with c-axis polarized optical phonons is virtually unscreened since the upper limit for the out-of-plane plasmon frequency in cuprates is well below the characteristic frequency of optical phonons. Due to a poor screening, the magnetic interaction remains small compared with the Fröhlich EPI at any doping of cuprates. Combined with on-site repulsive correlations (Hubbard U) and short-range deformation (i.e acoustic phonon) and Jahn-Teller [4] EPIs, the unscreened long-range Fröhlich EPI binds oxygen holes into superlight intersite bipolarons [2, 5], which Bose-condense at very high temperatures [6].

Experimental evidence for exceptionally strong EPI is now overwhelming [1], so that the bipolaronic superfluid charged Bose gas could be a feasible alternative to the BCS-like scenarios of cuprates. The bipolaron theory predicted such key features of cuprate superconductors as anomalous upper critical fields [7], spin and charge pseudogaps [8], and unusual isotope effects [9] later discovered experimentally. The theory accounts for normal state kinetics, including the anomalous Hall-Lorenz numbers, high T_c values, specific heat anomalies of cuprates (for a review see [1]), and also for the d-wave checkerboard order parameter [10], the normal state Nernst effect [11] and diamagnetism [12].

Here I argue that the Bose-condensate tunneling into a normal cuprate semiconductor [13] accounts for both nil [14] and giant [15] proximity effects discovered experimentally in cuprates. Several groups reported that in the cuprate SNS junctions supercurrent can run through normal N-barriers as thick as 10 nm, if the barriers are made from a non-superconducting cuprate layer. Since the c-axis coherence length is only about 0.1 nm, these observations are in a strong conflict with the standard

BCS picture. Using the advanced molecular beam epitaxy, Bozovic et al. [15] demonstrated that the giant proximity effect (GPE) is intrinsic, rather than caused by any inhomogeneity of the barrier such as stripes, superconducting "islands", etc.

This unusual effect can be broadly understood as the bipolaron BEC tunnelling into a cuprate semiconductor, Fig.1 [13]. The condensate wave function, $\psi(z)$, is described by the Gross-Pitaevskii equation [16] as

$$\frac{\hbar^2}{2m^{**}} \frac{d^2 \psi(z)}{dz^2} = [V|\psi(z)|^2 - \mu]\psi(z), \quad (1)$$

where V is a short-range repulsion of bosons, and m^{**} is the boson mass along the direction of tunnelling z . If the normal barrier, at $z > 0$, is an underdoped cuprate semiconductor above its transition temperature, the chemical potential μ is found below the quasi-2D bosonic band at a very small energy, Fig.1,

$$\epsilon = -k_B T \ln[1 - \exp(-T_0/T)]. \quad (2)$$

Here $T_0 = \pi \hbar^2 x' / k_B m^{**} \gg T'_c$ is much higher than the transition temperature, T'_c , of the barrier with the carrier density x' . Hence Eqs.(1,2) predict the occurrence of a new length scale, $\hbar / (2m^{**}\epsilon)^{1/2}$, which is much larger than the zero-temperature coherence length in a wide temperature range $T'_c < T < T_0$, accounting for GPE.

The physical reason why the quasi-2D bosons display a large normal-state coherence length, whereas 3D Bose-systems (or any-D Fermi-systems) at the same values of parameters do not, originates in the large density of states (DOS) near the band edge of two-dimensional bosons compared with 3D DOS. Since DOS is large, the chemical potential is pinned near the edge with the exponentially small magnitude, ϵ , at $T < T_0$. Importantly if the barrier is undoped ($x' \rightarrow 0$) ϵ becomes large at any finite temperature, which explains the nil proximity effect [14] in the case of the undoped insulating barrier.

I also argue that a huge anisotropy of the sound speed in layered superconductors makes the acoustic phonon-mediated attraction of electrons non-local in space providing unconventional Cooper pairs with a nonzero orbital momentum in the weak-coupling BCS regime [17]. As a result of this anisotropy quasi-two dimensional

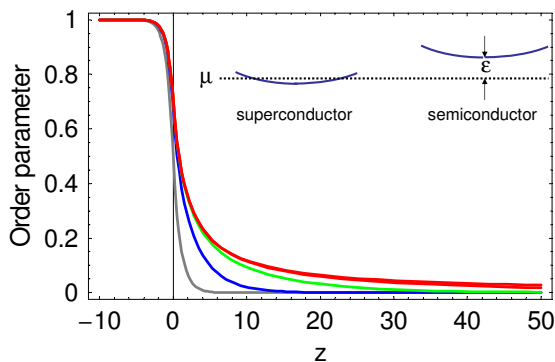


FIG. 1: BEC order-parameter near the SN boundary for different doping levels of the normal barrier at $z > 0$ (z is measured in units of the zero-temperature coherence length of the superconductor, the upper curve corresponds to a smallest ϵ , after Ref. [13]. The chemical potential is found above the boson band-edge due to the boson-boson repulsion in cuprate superconductors and below the edge in cuprate semiconductors with low doping.

charge carriers weakly coupled with acoustic phonons undergo a quantum phase transition from a conventional s-wave to an unconventional d-wave superconducting state with less carriers per unit cell. In the opposite strong-coupling regime rotational symmetry breaking appears as a result of a reduced Coulomb repulsion between unconventional bipolarons compared with the repulsion of less extended s-wave pairs dismissing thereby some constraints on unconventional (internal) symmetry of pre-formed pairs in the BEC limit as well.

The conventional acoustic phonons, and not superexchange [3], are shown to be responsible for the unconventional symmetry of cuprate superconductors, where the on-site Coulomb repulsion is large [17].

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